Influence of Variation in Sediment Conditions on the Acoustic Response of Targets near the Sea Floor

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Award Number: N00014-10-1-0394
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LONG-TERM GOALS

This project investigates the problem of detection and classification of mines and mine-like objects in contact with the sea floor. In these situations, not only is the acoustic response dependent on the objects elastic and geometric properties, but also on the properties of the surrounding environment and its specific location within that environment, i.e. proud, partial- or full-burial. The long-term goal is to identify the major factors, both target and environment related, that drive the acoustic response of the target. Once these have been identified, the goal is to develop simple models to predict the target response as its deployment in the environment changes.

OBJECTIVES

The development of effective detection and classification schemes for objects in contact with the sea floor must address the fact that the response of a target is unique only to the specific environment in which it is located. With this in mind, the objectives of this project were three-fold: (I) design and acquisition of experimental data that investigated the role played by the sediment, and more specifically the location of the target within the sediment, (II) development of finite element (FE) models that, validated by the experimental data, provide insight into the physics governing the response of the target, all leading up to (III) the development of simple models to predict the evolution of prominent phenomena observed in the target response as deployment conditions change.

APPROACH

Experimental and modeling efforts were combined to accomplish the objectives of this project. The first year FY10 focused on the acquisition of good experimental data that investigated targets in various deployment conditions within an underwater environment. The experiments, also referred to as PondEx10, were conducted in a fresh-water pond facility at the Naval Surface Warfare Center Panama City Division. The pond is 110 m long and 80 m wide, filled with approximately 9 million gallons of water, and has a 1.5 m layer of sand making up the bottom. Data acquisition is achieved through the use of a rail and mobile tower system. The tower houses an array on which sources and receivers are mounted, and transverses a distance of 19.1 m down the rail, the source pinging approximately once every 2.5 cm. For a schematic of the experimental setup, or additional details regarding the data acquisition and processing, refer to [1,2].

While a number of targets were used during PondEx10, only a subset was chosen as the focus of this particular project. These included a 1 ft diameter, 2 ft long solid aluminum cylinder, a 1 ft diameter, 2 ft long aluminum pipe having wall thickness of 3/8 in., two solid aluminum and steel replicas of an unexploded ordnance (UXO) artillery shell measuring 1.4 ft long and 4.2 in. in diameter, in addition to the real UXO artillery shell from which the replicas were made. The UXO were of particular interest since they had desirable attributes, such as fine details in the structure and different material composition, which made it possible to investigate the impact of variations in target shape and material on the acoustic response. These targets were deployed 5 and 10 m from the rail, and in both proud, partially- and fully-buried configurations.

Following the acquisition of experimental data, the primary approach during FY11 transitioned to the development of models for the water-filled pipe and UXO replicas for which experimental data acquired in FY10 could be used for validation. The specific models developed were chosen so as to investigate the role played by the target physics, and the target's deployment within the environment. A hybrid 2-D/3-D modeling technique was utilized here and exploits the axial symmetry of the target by decomposing the full 3-D problem into a series of 2-D azimuthal Fourier modal sub-problems [3,4]. The hybrid label refers to the fact that two separate modeling techniques are used to handle the local target response and the propagation to the far field. For the target piece, the 2-D Fourier sub-problems are solved using the commercially available finite element (FE) tool COMSOL, the result of which yields the pressure and its derivative local to the target surface. The 3-D propagation piece is accomplished through MATLAB scripts written to extract from the FE model the pressure and derivatives local to the target and propagate them to a desired location in the far field via the Helmholtz integral. Further details of this modeling technique can be found in [5]. The hybrid 2-D/3-D FE technique has a number of advantages, the first being the reduced computation time. Solving a 2-D axisymmetric problem, with degrees of freedom (dofs) typically on the order of 50 to 100K, is much faster than the equivalent full 3-D problem, generally on the order of millions of dofs. Another advantage, resulting specifically from the modal decomposition method, is that it allows one to examine the details of individual resonant modes of the target, which can be extremely useful when interpreting the role played by the target physics.

During the last few months of the project, a significant effort was made to couple the FE calculations with a simple acoustic ray-based wave propagation model. The FE model is used to calculate the free field scattering amplitude in the usual manner described above. The ray-based model uses image sources/receivers to define the ray paths, which include the multipath contributions. Since one of these paths is bistatic, the scattering amplitude out of the plane defined by the incoming wave vector and the target axis must be known. It was necessary therefore to run the FE calculations such that the scattered amplitude over a grid of points covering a hemispherical surface surrounding the target was obtained. Finally, the scattered pressure is calculated from the convolution of the source signal traveling along the ray path with the free field scattering amplitude obtained from the FE calculation. Following the initial investment of 15 days (on 5 cpus) for the free field FE calculation, the ray-based model can generate an acoustic template for any range/grazing angle in 0.1 minutes. Running the equivalent simulation with the Helmholtz propagation model would take 624 minutes. This fast ray-based model is used to study the acoustic response of targets at ranges varying from 5 to 50 m, ultimately leading to interpretations and predictions as to how prominent phenomena in the acoustic template evolve as a function of range.

Key Individuals:
Dr. Aubrey L. España is the principal investigator in this project. Drs. Kevin L. Williams and Steven G. Kargl provided insight and guidance pertaining to the experimental aspects of this work. Dr. Kargl also conducted the recent work on coupling the FE results to a ray-based propagation model. The finite element models were developed in collaboration with Dr. Mario Zampolli (Grant#: N62909-10-1-7153), previously at TNO Defense Security and Safety. Dr. España spent one month at TNO during the spring of 2011, while Dr. Zampolli visited APL-UW in Fall 2011 for 2 weeks. Dr. España also spent a few months each year at NSWC PCD to work with Drs. David S. Burnett and Joseph Lopes in conducting comparisons between hybrid 2-D/3-D model results (APL and TNO) and full 3-D model results (NSWC).

WORK COMPLETED

The work completed is categorized according to the three objectives of this project, namely (I) the environment, and target's deployment within that environment, (II) issues associated with the target itself and the physics governing its response, and finally (III) the predictions that can be derived due to the insight gained in I and II.

I. Environment:

1. Experimental data was acquired for targets in the free field, proud on a sand sediment, and in contact with interfaces of different materials, the goal being to learn how variation in the reflection coefficient affects the measured acoustic response (see annual report for FY10 [6]).
2. Experimental data and hybrid 2-D/3-D FE models were developed for the aluminum UXO replica in the following deployment conditions within the environment: (a) proud at a 10 m range from the source/receiver array, (b) proud at a 5 m range from the source/receiver array, and (c) buried 1 mm below the interface at a 5 m range from the source/receiver array. The grazing angle of the incident sound beam in the buried experiment is 38.7 degrees, and thus corresponds to supercritical incidence.
3. Free field FE simulations were conducted to obtain the scattered acoustic field covering a hemispherical surface for the solid aluminum cylinder, aluminum pipe, and aluminum UXO replica. These calculations were used in a ray-based propagation model that simulates a circular synthetic aperture sonar (CSAS) experiment, the result of which yields the scattered acoustic response at any desired range/grazing angle in less than a minute.

II. Target Physics:

1. A reversible SAS deconvolution algorithm was used to study the elastic response of the scattering from the aluminum pipe. This algorithm, the details of which are discussed in [7], functions by applying a mask in the image domain in order to extract desired regions of the target response. In this context, it was used to study the spectral and elastic responses, separately, of the aluminum pipe in the free field and proud on a sand sediment, the results of which are discussed in [8].
2. Hybrid 2-D/3-D FE models were developed to investigate how important the fine structure of the aluminum UXO replica is in regards to its acoustic response as embodied in the acoustic template. The simulation was for PondEx10 geometry, having the UXO deployed 10 m from the rail in a proud configuration. First, a simplified shape was used, in which all of the ridges and grooves in the exterior of the UXO body were removed, thus leaving a smooth exterior surface. Next, the exact shape of the UXO was modeled, which included all of the ridges and

grooves. Acoustic templates for these two models are compared to experimental data acquired during PondEx10, and are discussed in detail in the annual report for FY11 [9].

3. MATLAB scripts were developed that extract the pressure derivatives (dp/dn) from the FE model either on or near the target surface, and create a deformed surface displacement plot. Since dp/dn is proportional to the surface displacements, these plots are essentially illustrating the motion of the target as it is excited by the incident sound wave. The visualization uses a color surface plot of the magnitude of dp/dn, coupled with arrows to depict the direction of motion of the surface. An example is shown below in this report, as well as in [5].

<u>III. Predictions</u>:

1. The evolution of the coupling angle for sound into bending modes of the solid aluminum UXO replica is explained via a simple geometrical model.
2. A simple model is developed to predict the appearance of nulls at specific frequencies in the acoustic template. The particular null investigated arises due to the interference of the direct and double-bounce ray paths. A similar technique can be applied to investigate the interference between the single-bounce path and the direct and double-bounce.

RESULTS

Figure 1 illustrates the effect that the presence of the sediment has on the measured acoustic scattering from an object, in this case the aluminum pipe. The target strength is plotted as a function of azimuthal rotation angle and ka for: **(a)** a free field experiment conducted in a large tank at Washington State University, and **(b)** the pond experiment (PondEx10) for the pipe in a proud configuration on the sand sediment, at a range of 10 meters from the rail. Broadside corresponds to a rotation angle equal to 0 deg. and end-on is 90 deg. The added presence of the sediment brings about multipaths that sound can follow between the target and interface, ultimately altering how the sound couples to and interacts with the target. This is seen in the existence of a number of bright phenomena that were otherwise not visible in the acoustic response of the target in the free field, specifically in the region from about 10-20 deg. and 45-75 deg. The results of the hybrid 2-D/3-D FE calculations for the aluminum pipe are shown in **Fig. 1** for **(c)** the free field configuration in the tank experiment, and **(d)** in the proud configuration of PondEx10. The hybrid 2-D/3-D FE model succeeds in capturing the response of the target that was observed in the experiments. Note that some of the sharp resonances observed in the model template are not present in the data. These are high-Q resonances that require a long pulse to ring up, and thus are not excited in the experiment, which has a finite pulse length. Furthermore, the discrepancy between the proud data and model templates at low frequency is known to be due to scattering from the sediment itself. This is something that is not included in the FE model, and hence does not appear in the acoustic template.

Figures 2 (data from PondEx10) and **3** (model results) illustrate how the target response is affected by the specific burial state and range. In each of these figures, (a) corresponds to the aluminum UXO replica proud at 10 m range, (b) proud at 5 m range and (c) fully-buried, 1mm below the surface, at 5 m range. Here, 0 deg. has the UXO's tail towards the source, while 180 deg. is nose-on. Comparison of the data templates with their respective model templates reveals that the models are capturing the overall response of the target very well. The models accurately predict the brightest, most prominent phenomena observed in the data. Another important observation arises by watching the evolution of the bright resonant peaks, centered approximately at 7, 9 and 11 kHz, as the transition from proud at 10 m, to proud at 5 m and finally buried at 5 m is made. As the source moves closer to the target, the azimuthal angle required to couple into the resonant modes shifts to an angle closer to either the nose

or tail of the target. This type of effect can be predicted with a fairly simple geometrical transformation, and is discussed in further detail below.

Figure 4 illustrates the advantage of using the Fourier modal decomposition method, depicting the acoustic templates for the aluminum UXO replica on a mode-by-mode basis. Examination of these templates reveals that while the broadside response (90 deg.) is made up of multiple modes, most of the off-axis response is driven by only one or two modes. This is seen in the tail-on (0 deg) and nose-on (180 deg.) response, which is only present in the mode 0 template, and the sharp resonant peaks at 40 and 140 deg. in the mode 1 template. Another advantage of using the hybrid 2-D/3-D FE model lies in the fact that the pressure derivatives (dp/dn) are sampled on or near the target surface. This allows for plots to be generated of the surface displacement (proportional to dp/dn) and can help to visualize the vibration of the target at specific resonances. This is illustrated in **Fig. 5**, in which the response of the target at the resonant peak, located at 40 deg and 6.8 kHz is depicted. The magnitude of dp/dn is plotted on a color scale, while the arrows show their direction. The arrows are automatically scaled so as not to overlap. **Figure 5** corresponds to **(a)** the sum over all modes, **(b)** mode 0, and **(c)** mode 1. This illustrates that the motion of the UXO at this particular resonance is a bending mode.

Recent progress made in coupling the FE results with a simple ray-based propagation model is illustrated in **Fig. 6**. These are plots of the target strength as a function of frequency and rotation angle for the aluminum UXO replica proud on a sand sediment at ranges **(a)** r = 5 m, **(b)** r = 6 m **(c)** r = 7 m, **(d)** r = 8 m, and **(e)** r = 9 m. Some observations that stand out include the movement of the sharp resonant peaks, previously determined to be associated with a bending motion of the target (mode 1). At close range (r < 8 m), the target must be either tail or nose-on in order for sound to couple into the resonances. As the source moves out in range, this coupling angle shifts by as much as 40 deg. The coupling condition for these resonances is understood through a simple geometrical transformation, and amounts to calculating the angle that the incoming sound has with respect to the normal at the target surface in the plane containing the incident wave vector and target normal. Details of this derivation are given in the appendix of [1]. Another prominent effect is the null observed in the acoustic template and its movement as the range is increased. The null arises to due to the interference between the various paths available, namely direct (path 1), single-bounce (path 2) and double-bounce (path 4). Understanding exactly how all of the relative phases will sum up to produce either peaks or nulls is complicated. Thus, it is advantageous to first investigate the interference of only two of these features. **Figure 7** shows the acoustic template resulting from only the direct and double-bounce paths for ranges **(a)** r = 7 m, **(b)** r = 9 m, **(c)** r = 17 m, and **(d)** r = 38 m. In each of these there is at least one dark null visible that spans the entire angle range. By keeping track of the relative phase difference between the direct and double-bounce path, and accounting for the reflection coefficient of the water-sediment interface, it is possible to derive a simple equation that can predict the location of the nulls as a function of range to the target, illustrated in **Eq. 1** below,

$$\frac{2\pi f}{c}\Delta PL + 2\phi_{RF} = (2n+1)\pi \qquad (1)$$

where f is the frequency, c is the water sound speed, ϕ_{RF} is the phase of the sediment reflection coefficient, and ΔPL is the difference in path length between the path 1 and path 4 rays and is where the range dependence comes in. **Figure 8** plots the predicted null locations according to **Eq. 1** above, for n = -1, 0 and 1. The markers correspond to locations of the nulls in **Fig. 7**, and lie directly on the prediction curves.

IMPACT/APPLICATIONS

This research helps explain the acoustic response of targets on or embedded in a sand sediment. The acoustic scattering in these situations is highly dependent on the target physics, environment properties, and ultimately how the target is oriented within the environment. While these driving forces cannot be decoupled from each other, this project has succeeded in outlining experimental and modeling techniques that serve to identify the role played by each in building up the final acoustic response. Steps have been taken to develop simple models to predict changes in the acoustic template arising from different target deployment conditions within the environment. This is important progress that ultimately allows for robust, quick predictions to be made for different target configurations, removing the requirement for running computationally and financially expensive simulations and/or experiments. Models that can successfully predict the target response in the environment, such as those discussed here, can be used to build feature-sets for use in classification algorithms, and will be a big focus in FY12-14.

RELATED PROJECTS

"High Fidelity Finite Element Modeling for the Identification of Low- to Mid-Frequency Proud and Buried Object Elastic Responses and SAS Image Features," ONR NICOP Grant#: N62909-10-1-7153, PI: Dr. Marten J. J. Nijhof (TNO).

"Acoustic Color of mines and mine-like objects: Finite Element Modeling (FEM), Developing Automatic Target Recognition (ATR) strategies, and at-sea experimental validation," ONR Contract #: N00014-07-G-0557/0032, PI: Dr. Kevin L. Williams (APL-UW).

"Reverberation, sediment acoustics, and targets-in-the-environment," ONR Grant #: N00014-11-1-0428, PI: Dr. Kevin L. Williams (APL-UW).

"Acoustic Response of Underwater Munitions Near a Sediment Interface: Measurement-Model Comparisons and Classification Schemes," SERDP Contract #: W912HQ-12-C-0016, PI: Dr. Steven G. Kargl (APL-UW).

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[5] M. Zampolli, A.L. España, K.L Williams, S.G. Kargl, E.I. Thorsos, J.L. Lopes, J.L. Kennedy, P.L. Marston, "Low- to mid-frequency scattering from elastic objects on a sand sea floor: Simulation of frequency and aspect dependent structural echoes," J. Comput. Acoustics, invited paper (accepted 12/7/2011).
[6] A. L. España, "Influence of Variation in Sediment Conditions on the Acoustic Response of Targets near the Sea Floor," Annual Report for ONR Award #: N00014-10-1-0394, (2010).
[7] Timothy M. Marston, Philip L. Marston, and Kevin L. Williams, "Scattering resonances, filtering with reversible SAS processing, and applications of quantitative ray theory," Proc. MTS/IEEE OCEANS Conf., (2010).
[8] A. L. España, K. L. Williams, S. G. Kargl, M. Zampolli, T. M. Marston, and P. L. Marston, "Measurements and modeling of the acoustic scattering from an aluminum pipe in the free field and in contact with a sand sediment," Proc. MTS/IEEE OCEANS Conf., (2010).
[9] A. L. España, "Influence of Variation in Sediment Conditions on the Acoustic Response of Targets near the Sea Floor," Annual Report for ONR Award #: N00014-10-1-0394, (2011).

PUBLICATIONS

A. L. España, K. L. Williams, S. G. Kargl, M. Zampolli, T. M. Marston, and P. L. Marston, "Measurements and modeling of the acoustic scattering from an aluminum pipe in the free field and in contact with a sand sediment," Proc. MTS/IEEE OCEANS Conf., (2010).

M. Zampolli, A.L. España, K.L Williams, S.G. Kargl, E.I. Thorsos, J.L. Lopes, J.L. Kennedy, P.L. Marston, "Low- to mid-frequency scattering from elastic objects on a sand sea floor: Simulation of frequency and aspect dependent structural echoes," *J. Comput. Acoustics*, invited paper (accepted 12/7/2011).

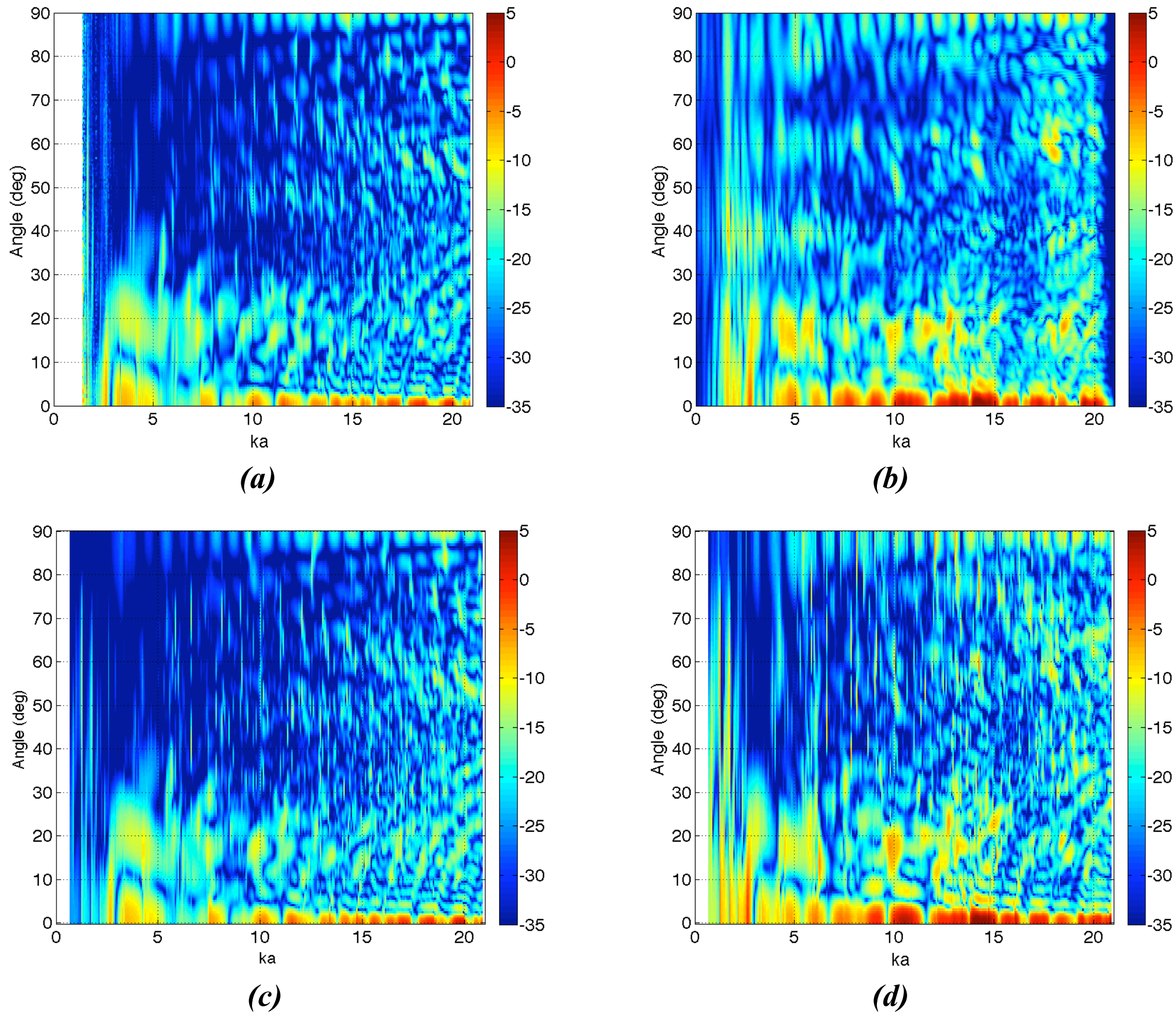

Figure 1. Target strength as a function of ka and azimuthal rotation angle for a water-filled aluminum pipe (a) acquired during a free field tank experiment, (b) acquired during PondEx10, proud 10 m from the rail, (c) hybrid 2-D/3-D FE model for the free field experiment in (a), and (d) hybrid 2-D/3-D FE model for the proud experiment in (b).

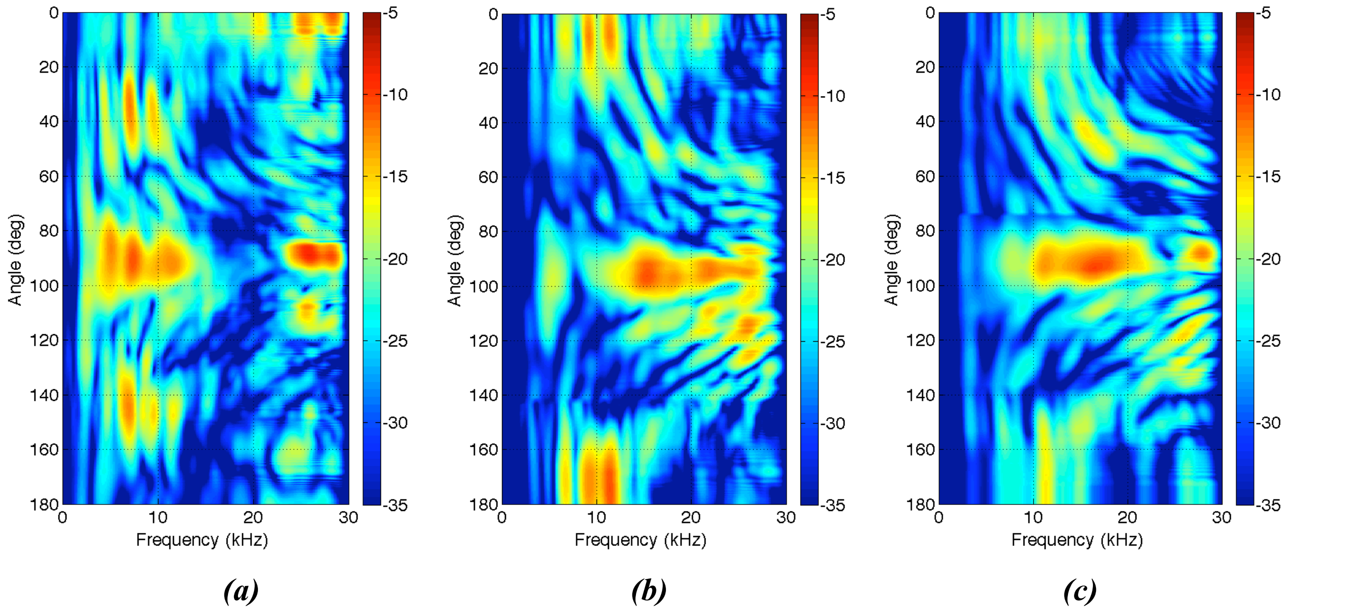

Figure 2: Acoustic templates generated from the data acquired during PondEx10 for the aluminum UXO replica (a) proud at a range of 10 m from the rail, (b) proud at a range of 5 m from the rail, and (c) buried 1 mm below the sand at a range of 5 m from the rail.

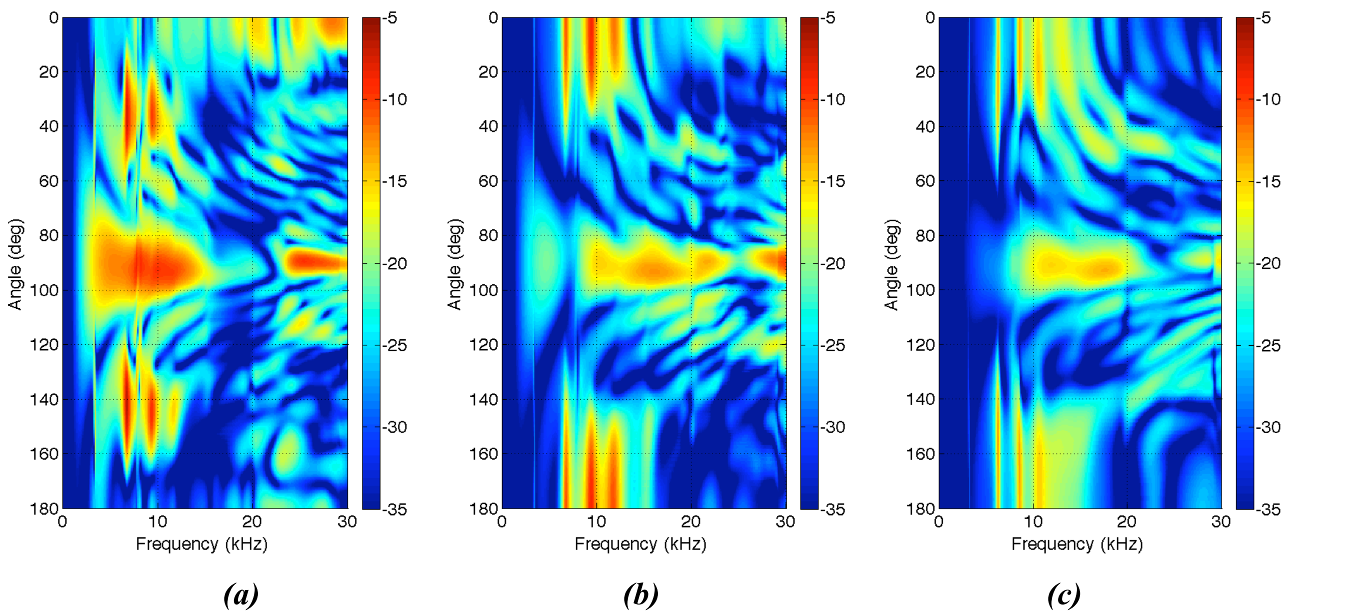

Figure 3: Acoustic templates for the aluminum UXO replica generated from the hybrid 2-D/3-D FE model, corresponding to the experimental geometry utilized during PondEx10 and for the same deployment conditions as Fig. 3, given by (a) proud at 10 m range, (b) proud at 5 m range, and (c) buried at 5 m range.

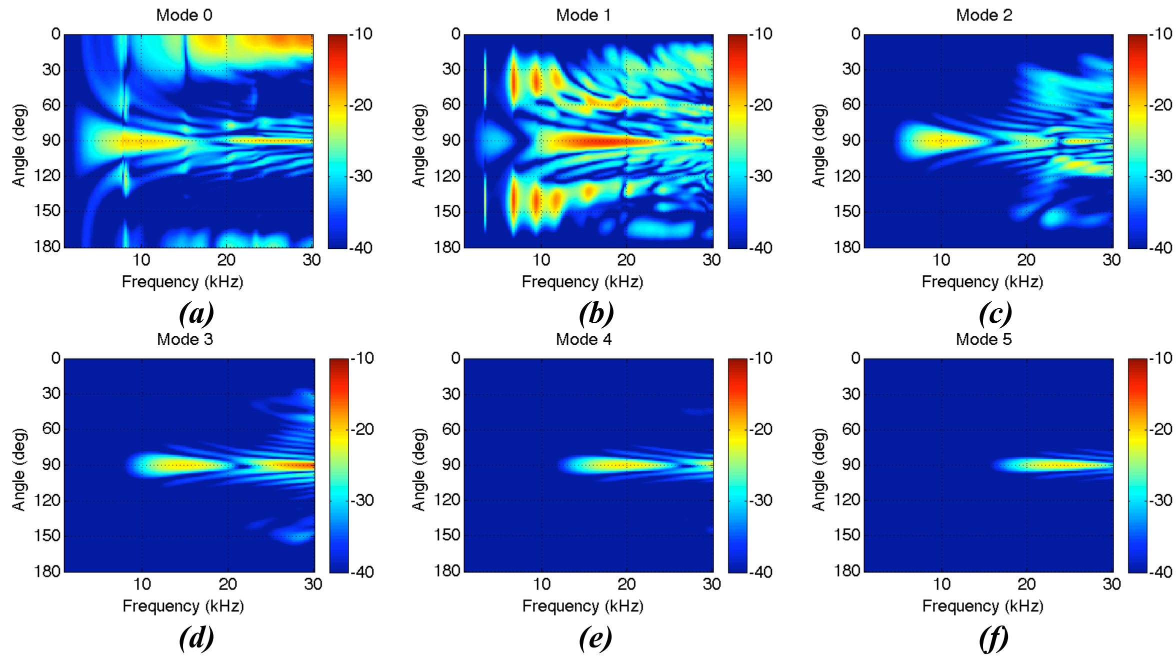

Figure 4. Plots depicting the modal decomposition of the target strength as a function of frequency and angle for the hybrid 2-D/3-D FE model results for the aluminum UXO replica in the free field, where each plot corresponds to (a) mode 0, (b) mode 1, (c) mode 2, (d) mode 3, (e) mode 4, and (f) mode 5.

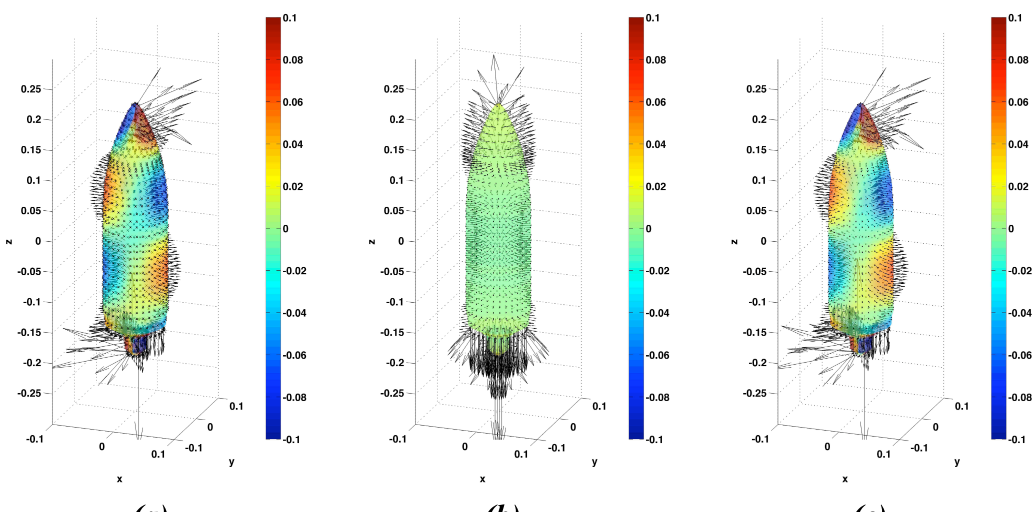

Figure 5. Plots depicting the normal pressure derivatives (dp/dn) on the surface of the UXO at an angle of 40 deg. and a frequency of 6.8 kHz, calculated using the hybrid 2-D/3-D FE model. (a) Corresponds to the total response, or the sum over all Fourier modes, (b) is just Fourier mode 0, and (c) is mode 1. The color scale indicates the magnitude of dp/dn, while the arrows give the direction. The arrows have been automatically scaled so as not to overlap.

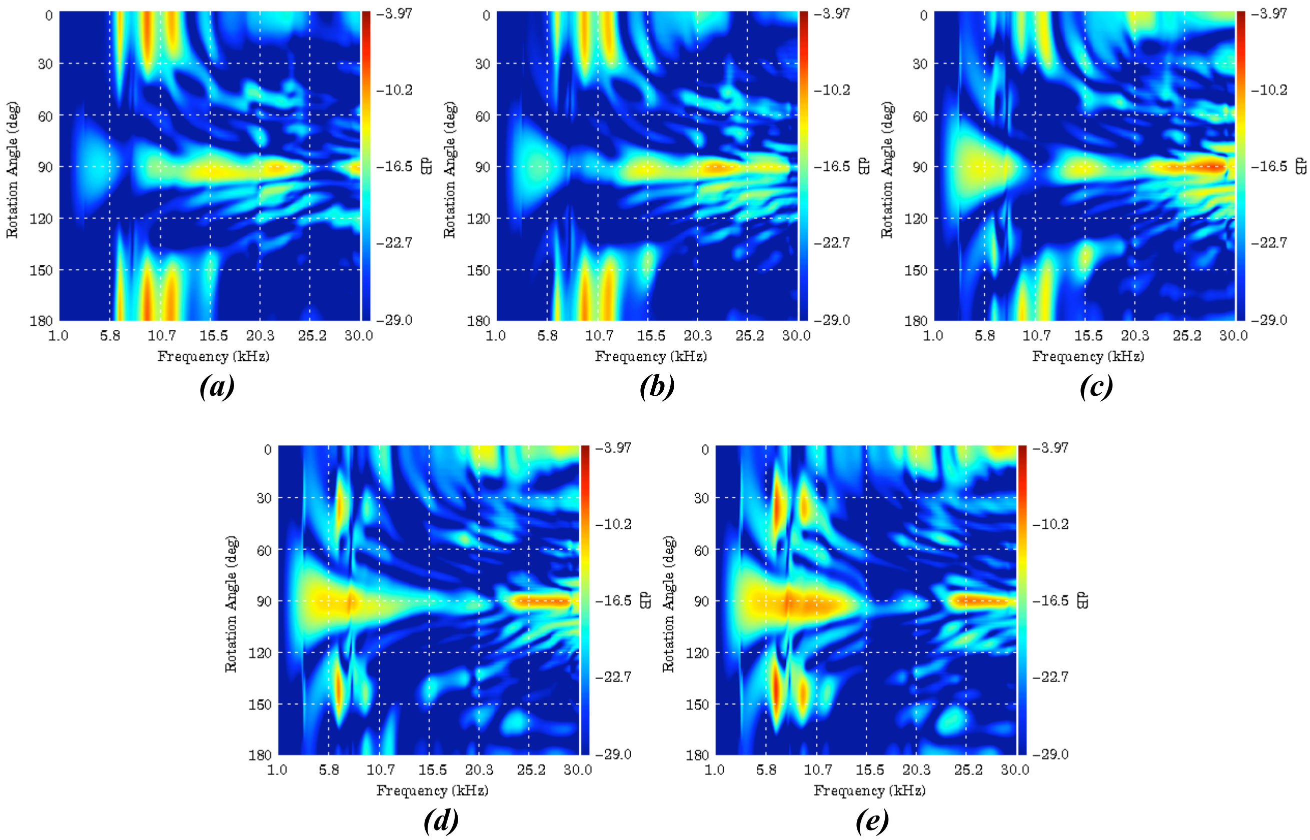

Figure 6. Target strength as a function of frequency and target rotation angle, calculated via the FE/ray-based propagation model, for the aluminum UXO replica proud on a sand sediment at ranges (a) r = 5 m, (b) r = 6 m (c) r = 7 m, (d) r = 8 m and (e) r = 9 m.

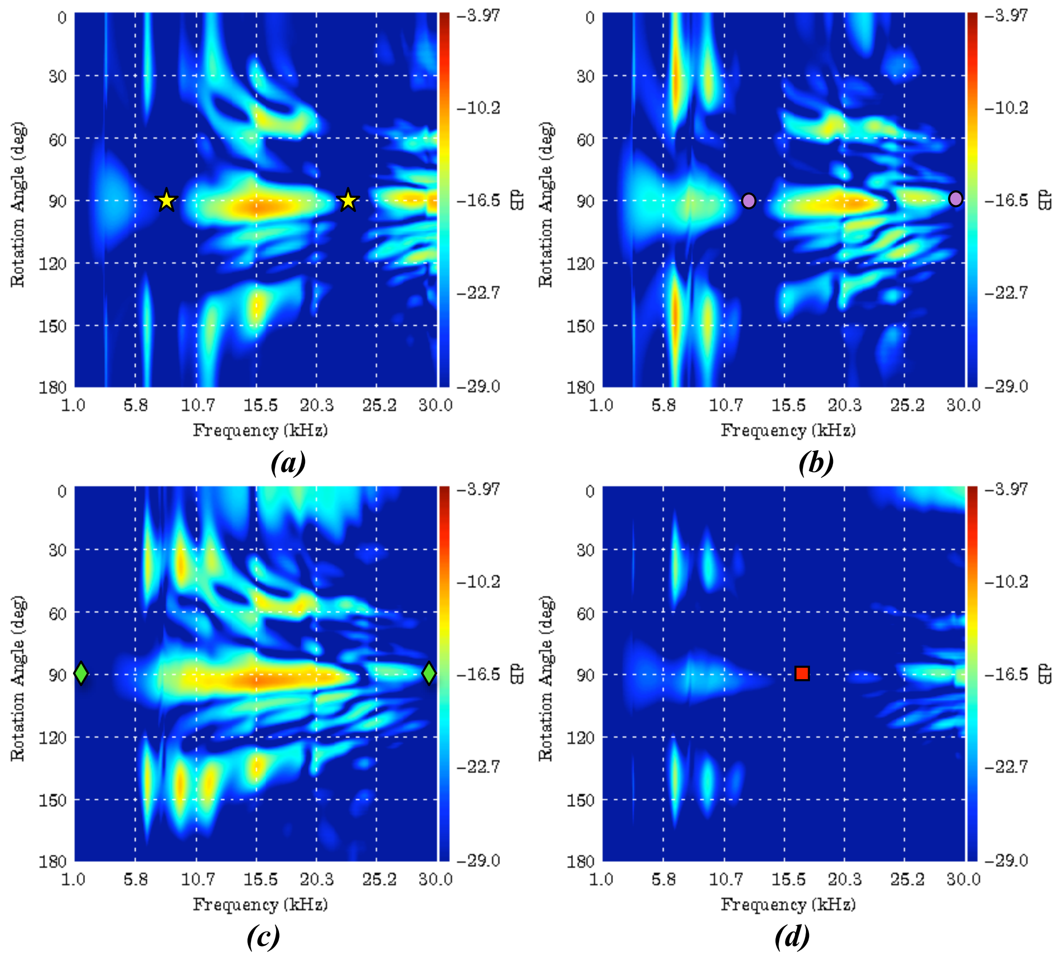

Figure 7. Target strength resulting from paths 1 (direct) and 4 (double-bounce), calculated via the FE/ray-based propagation model, for the aluminum UXO replica proud on a sand sediment for ranges (a) r = 7 m, (b) r = 9 m, (c) r = 17 m, and (d) r = 38 m.

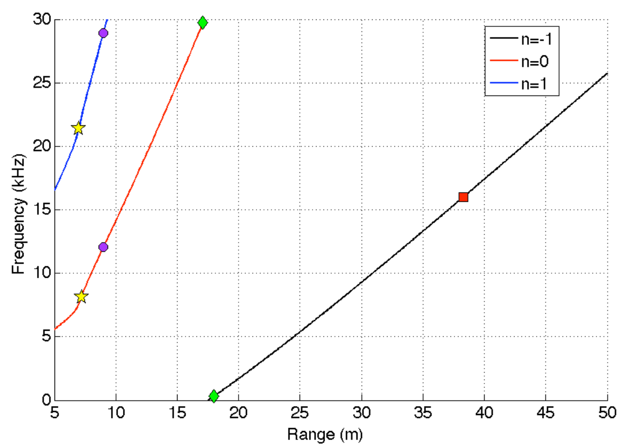

Figure 8. Predictions for the location of the null represented by Eq. 1, which arises from the interference of the direct path and double-bounce path. The markers correspond to the locations of the nulls observed in Fig. 7 for (a) r = 7 m (yellow stars), (b) r = 9 m (purple circles), (c) r = 17 m (green diamonds), and (d) r = 38 m (red square).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
25-06-2012	Final Technical Report	01 Jan 2010 - 31 Mar 2012

4. TITLE AND SUBTITLE
Influence of variation in sediment conditions on the acoustic response of targets near the sea floor

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-10-1-0394

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release, Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
acoustic response, sediment variation, acoustic scattering

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	12	Aubrey Espana
					19b. TELEPHONE NUMBER *(Include area code)* (206) 685-2311

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